An Inflatable/Self-Rigidizable Structure for the Reflectarray Antenna

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1. Introduction

An innovative inflatable/self-rigidizable structure has been developed for the Ka-band (32 GHz) three-meter reflectarray antenna [1]. Although this kind of antenna is primary developed for space applications to achieve very low mass and small launch-vehicle stowage volume, it can also be employed for ground and sea-based applications. The basic electromagnetic component of this kind of antenna is a flat membrane with several hundred thousand of copper patches. The membrane is supported by an inflatable/self-rigidizable frame structure. The inflatable/self-rigidizable structure can be flattened and both the flattened structure and the membrane are rolled up on a mandrel. After the antenna is brought to the site, it is inflation deployed and the dynamics of the deployment is controlled by the deployment control system. Compare to other kinds of deployable antennas, this kind of antenna is very lightweight and its package is very efficient. It is very economical for space, ground, and sea-based applications.

The development of inflatable structures has had a long history. This kind of structure used as electromagnetic supporting structures have been extensively investigated recently [2]. Major challenges include controlled deployment, space rigidization, dynamic modeling and simulation, etc. With the development of inflatable technologies, inflatable structures used as electromagnetic structures are becoming very possible for near-term space missions.

The new technology, namely beam scanning reflectarray antenna with circular polarization [3], made it possible to use a flat surface instead of a parabolic surface as the electromagnetic component. A flat "natural" thin-membrane surface is much easier to accomplish and maintain than a curved "non-natural" parabolic surface. It is also believed that a flat surface has better reliability for a long-term space mission than a thin membrane parabolic surface.

This paper will start from the reviewing of previous developments of the inflatable reflectarray antenna. Details of the current model will then be presented. Functions of several major components and future development directions will also be discussed.

2. Previous Developments of the Inflatable Reflectarray Antenna

The development of this technology started from a one-meter model of the inflatable reflectarray antenna [4]. Figure 1 is the picture of this one-meter inflatable reflectarray antenna. The diameter of the electromagnetic area is one meter. The inflatable structure of the antenna is made of Urethane coated Kevlar. Urethane coated Kevlar is a very strong material for holding inside pressure. The electromagnetic membrane is made of Kapton. The weight of the inflatable structure is 0.74 kilogram and the weight of the electromagnetic film is 0.27 kilogram. The total weight of the whole antenna is only 1.08 kilogram.

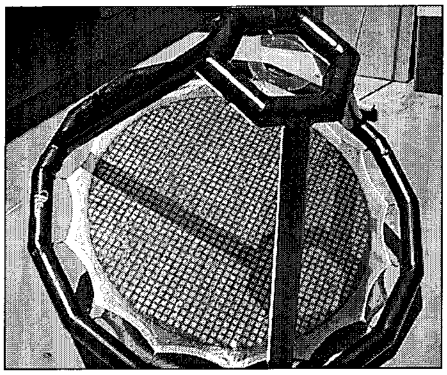

Figure 1. One-Meter Inflatable Reflectarray Antenna

Upon the great success of the RF test of the one-meter inflatable antenna, a three-meter technology demonstration model of the inflatable reflectarray was also developed [5,6]. The RF test results of the three-meter antenna demonstrated excellent radiation pattern characteristic. Figure 2 is the picture of the 3-meter inflatable reflectarray antenna and Figure 3 gives the drawing of the antenna. The configuration of this antenna is like a horseshoe and its feed is supported by three asymmetrically located inflatable struts.

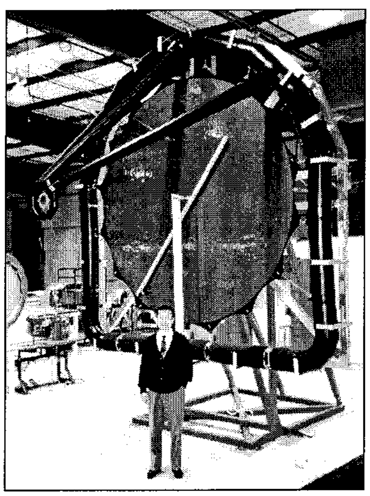

Figure 2. Three-Meter Inflatable Reflectarray Antenna

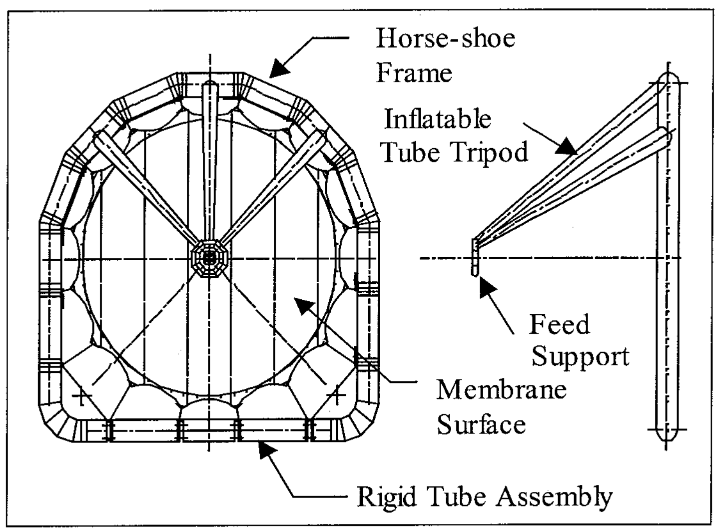

Figure 3. Drawing of the Three-Meter Inflatable Reflectarray Antenna

The reason to change the configuration from circular to horseshoe is that, after the inflatable structure is deflated, the membrane and the deflated structure can be rolled up onto the Rigid Tube Assembly without any damage. The tripod as well as the top portion of the horseshoe is made of Urethane coated Kevlar and the weight is 3.92 kilograms. The electromagnetic membrane is made of Kapton and the weight is 2.55 kilograms. The Rigid Tube Assembly is made of aluminum and the weight is 7.10 kilograms. The total weight of the antenna is only 13.57 kilograms.

However, this design has several disadvantages. The first disadvantage of this design is that the feed and its amplifiers are placed far away from the spacecraft, which is located just below the antenna (nearby the center of the rigid tube assembly). These amplifiers will be difficult to protect thermally from extremely cold temperature in space. Vibration of the feed supporting struts is another disadvantage of this design. RF blockage introduced by feed supporting struts is also a disadvantage of this design.

3. The "Movie Screen" Inflatable/Self-Rigidizable Reflectarray Antenna

In order to increase the readiness level for space application, a design trade study for the three-meter inflatable reflectarray antenna has then been conducted [7]. The "movie screen with offset feed array" was identified to be the best candidate for the reflectarray antenna structure. Based on the results of the design trade study, a new inflatable/self-rigidizable, namely "movie screen", reflectarray antenna has been developed. The feed of this unit is offset located on the spacecraft and the reflectarray surface is deployed up independently from the feed by two inflatable booms. Figure 4 demonstrates the deployment process of the "movie screen" antenna. The inflation deployment process only involves the unrolling and pressurization of two inflatable booms. Compare to a mechanically deployed counterpart, much less moving parts is employed by the inflatable structure. Less parts not only means less weight and less development cost, it also means less chances of deployment failure.

Figure 5 is the schematic of the "movie screen" inflatable reflectarray antenna. Major components include electromagnetic membrane, inflatable booms, rigid bars, roll-up shells, cross bars, constant force springs, mandrels, end caps, catenary systems, etc.

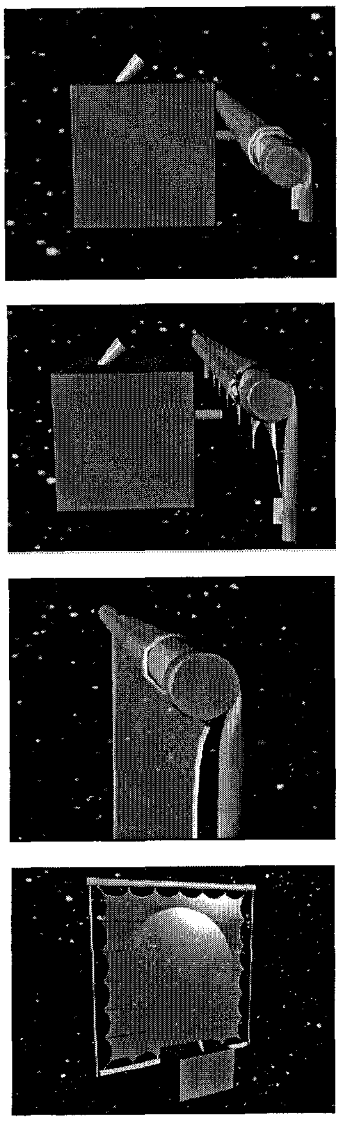

Figure 4. The Process of the Inflation Deployment

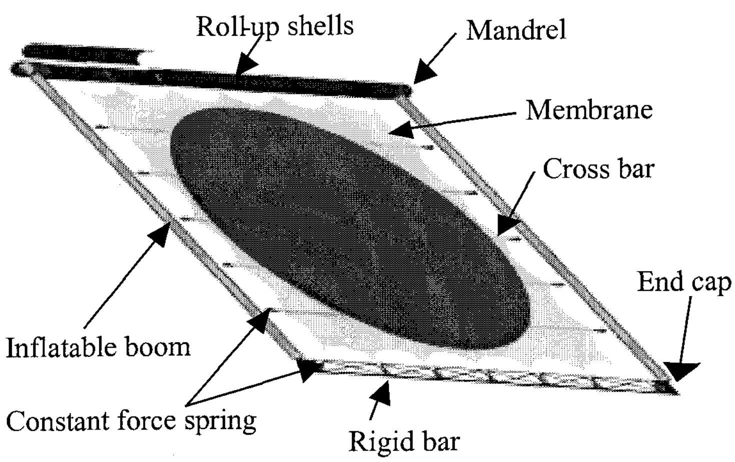

Figure 5. Schematic of the "Movie Screen" Inflatable Reflectarray Antenna

The design consideration of each component will be discussed as following.

a) Electromagnetic membrane

The most important component of the antenna is the electromagnetic membrane. Circular part at the center of the membrane carries the electromagnetic patches. Membrane around the electromagnetic section is used to connect the electromagnetic area to the structure. The whole structure is only designed to hold the membrane, to stretch the membrane, to avoid wrinkles on the membrane, and to keep the flatness of the membrane.

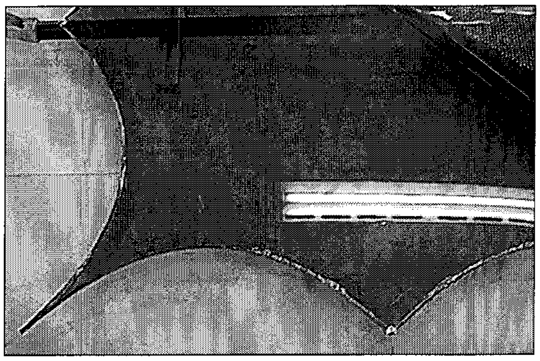

Figure 6. Catenary System

A catenary system around the membrane is used to attach the membrane to the structure and to uniformly tension it. Based on the required stress density (90 psi), the curvature of the catenary is calculated as a parabolic curve [8]. Tubings are attached to the edges of the membrane. A string inside the tubing is used to connect the membrane to the supporting structure. The string can freely slide inside tubings. Figure 6 shows the catenary system.

b) Constant force springs

The string of the catenary system is connected to 24 constant force springs. Constant springs are used to insure the stress distribution required for the membrane. Because of the constant force springs, stress distribution in the membrane will not be affected by the substantial temperature changes in the space. Using constant force springs significantly reduces the adjustments to achieve the proper tension of the membrane. 14 constant force springs are attached to the rigid bars and 10 constant force springs are attached to cross bars. Figure 7a shows how a constant force spring is attached to a rigid bar. Figure 7b shows how a constant force spring is attached to a cross bar.

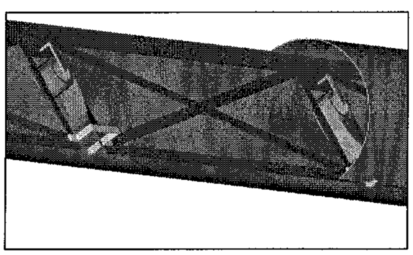

Figure 7a. A Constant Force Spring Attached To a Rigid Bar

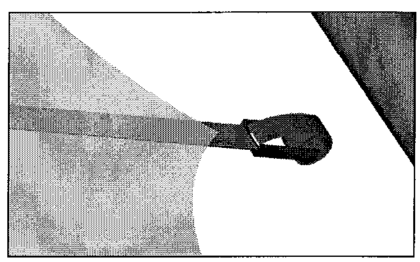

Figure 7b. A Constant Force Spring Attached To a Cross Bar

c) Rigid bars

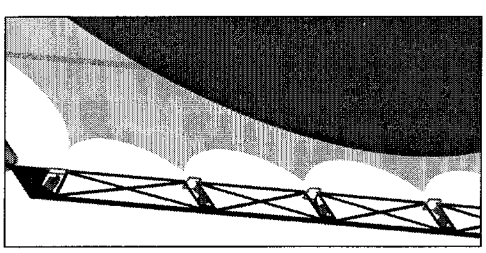

Figure 8. Rigid Bar Attached By Constant Force Springs

Two rigid bars are used at two ends of the antenna. They are made of carbon fiber and Figure 8 shows the rigid bar. Rigid bars have two functions. The first one is to provide attachment points for constant force springs. The second one is to resist bending loads created by constant force springs.

d) Roll-up shells

Rigid bars are covered by roll-up shells and both Figures 5 and 7a show the roll-up shell. The carbon fiber roll-up shells have two functions. One is to provide a surface for the electromagnetic membrane to be tightly rolled up, so the thin membrane will be able to survive the launching impact. The shells also act as structural members to provide bending and compression stiffness.

e) Cross bars

Due to the reason that inflatable booms cannot take bending loads, cross bars are employed as compression members to stretch the electromagnetic membrane. Each cross bar is made of carbon fiber tubing with an aluminum bracket at each end of the cross bar. Figure 7b shows how a constant force spring is installed on the aluminum bracket and attached to the electromagnetic membrane. Cross bars can be rolled up onto roll-up shells with the membrane.

f) Mandrels

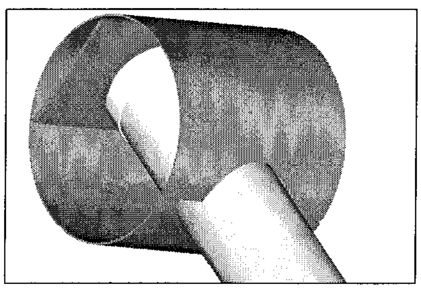

Figure 9. An Inflatable/Self-Rigidizable Boom Connected To A Mandrel

Mandrels have two functions. The first one is to connect inflatable booms to rigid bars and roll-up shells. The second one is to provide circular surfaces for inflatable booms. It is found [9] that the axial buckling capability of an inflatable/self-rigidizable boom after it is deployed is associated with the diameter of the mandrel while it is packaged. A mandrel is necessary to keep the diameter of the bundle to avoid the boom damage caused by the packaging. Figure 9 shows how an inflatable/self-rigidizable boom is connected to a mandrel.

4. Inflatable/Self-Rigidizable Technology

There is a major improvement of the "movie screen" antenna to the "horse-shoe" antenna. The "movie screen" antenna employed inflatable/self-rigidizable technology while the "horse-shoe" antenna only used inflatable technology.

Technically, the word "inflatable" means the structure is deployed by pressurization. After a structure is deployed, pressure still has to be kept inside the structure to maintain the rigidity of the structure. Due to the material imperfections and/or small damages caused by micro-meteoroids, small leaks are unavoidable. Large amount of make-up gas has to be carried to the space for a long-term mission, which is very costly or even not realistic.

With the development of space inflatables, space rigidization is becoming a major research topic. Space rigidization, namely inflatable/rigidizable, is that a structure is rigidized upon the completion of its inflation deployment. Several rigidization methods have been developed [2] and will be briefly discussed as following:

- Space cured polymers. This method includes the development of some polymers that can be cured by space environments, such as vacuum, ultraviolet light, infrared energy, and cold.
- Solvent loss system. This method uses the fabric that is impregnated with a volatile plasticizer (e.g. water). The volatile plasticizer leaves the fabric and makes it rigid as soon as the structure is deployed in the vacuum.
- Stretched aluminum laminate. The laminate is made of very thin aluminum foil with polyester films on both sides. While the polyester films provide tear resistance and gas seal, the aluminum foil is stretched by pressure just above the yielding point to provide the rigidity of the inflatable structure.
- Cold Hibernated Elastic/Shape Memory (CHEM). CHAM is formulated by incorporating shape memory polymers into open-cellular form. This material has a maximum deployed/stowed volume ratio of 30 and is self-expanding when heated up above its glass transition temperature. That means a space rigidizable structure made of CHEM does not need an inflation system to deploy.

Among all those rigidization methods mentioned above, stretched aluminum laminate is the only one that is not only inflatable/rigidizable, but also inflatable/self-rigidizable. Self-rigidizable means that it automatically rigidizes with no space power, curing agent, and rigidization system is required. However, due to packaging constraints, only a very thin (no more than 0.1 millimeter) soft aluminum layer can be incorporated in the laminate. Consequently, an inflatable/rigidizable boom made of stretched aluminum laminate can only take very low axial loading. Before the stretched aluminum laminate method can be really employed to real space missions, the load-carrying capability must be improved.

A new inflatable/self-rigidizable method, namely Spring Tape Reinforced (STR) aluminum laminate boom, has been developed by this research for the "movie screen" antenna [10].

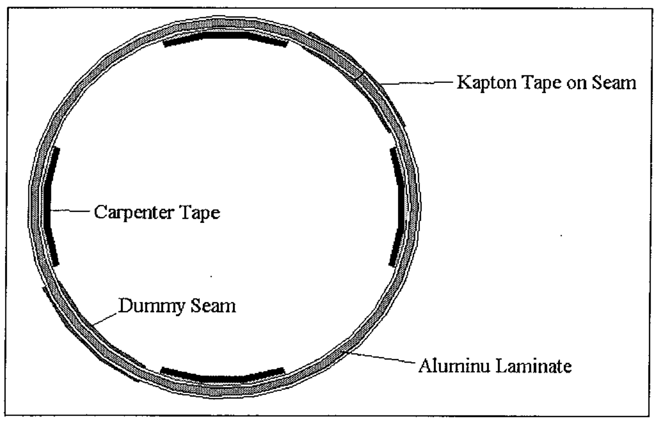

Figure 10. Cross-Section of a Typical STR Aluminum Laminate Boom

A typical STR boom consists of a tube that is formed with aluminum laminate. Figure 10 shows the cross-section of the STR aluminum laminate boom. Four spring tapes are attached to the inside wall of the tube in axial direction. At this time, the commercially available stainless steel measuring tapes, commonly known as carpenter tapes, are used. With a wall thickness less than 0.1 millimeter, a STR boom can be easily flattened, rolled-up (or folded-up), and deployed by a relatively low inflation pressure. The buckling capability of a STR aluminum laminate boom is significantly improved mainly due to the high modulus of elasticity and curved cross-sectional profile of the spring tapes. The length of a STR boom can consequently be significantly increased. It should be pointed out that spring tapes are very effective in resisting inward buckling and the aluminum laminate wall is very stable in resisting outward buckling. Therefore, these two components effectively complement each other in resisting local crippling of the boom. In addition, unlike the non-reinforced aluminum laminate booms, a STR aluminum laminate boom relies on the reinforcing tapes, not pre-strain induced by high internal pressure, to attain its post-deployment stiffness. The required inflation pressure for a STR aluminum laminate boom is relatively low. Several 5-meter long, 7.6-centimeter diameter booms have been assembled and tested. The weight of each boom is only 0.9 kilogram. The axial buckling load carrying capability of this kind of boom can reach 74 kilograms (with pin-pin boundary conditions).

5. Dynamic Analysis

The structure of the antenna is relatively large and flimsy. The dynamic characteristics of the inflatable/self-rigidizable structure have been questioned. In order to investigate the response of the structure to the excitation introduced by the spacecraft maneuvering, a finite element model has been made and the dynamic response analysis has been conducted. The membrane itself has very little out-of-plane bending stiffness. The-out-of plane stiffness of the membrane is from the pretensioning. It is the function of the membrane stress distribution and is called differential stiffness. Therefore, the dynamic response analysis of a membrane structure has three steps [11]. The first step is the static analysis to obtain the stress distribution, the second step is the modal analysis, and the third step is the response analysis.

A finite element with 568 nodes and 622 elements was assembled. The finite element software NASTRAN was used for the analysis. First of all, static analysis was performed to simulate the tensioning of the membrane and to obtain the differential stiffness. Stress distributions both in x direction (from left to right of the membrane) and y direction (from bottom to top of the membrane) were calculated and they were within the range of +/- 1 psi of the 90 psi (90 psi is design goal). Modal analysis, incorporating differential stiffness induced by pretension of the membrane, was also performed. Figures 11a and 11b give the first and second mode shapes of the antenna.

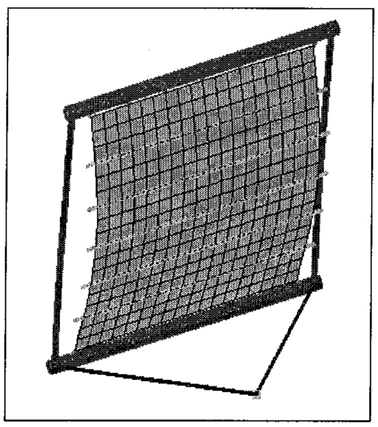

Figure 11a. First mode shape

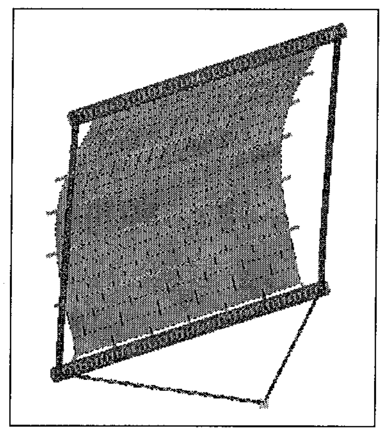

Figure 11b. Second mode shape

After the modal analysis, transient analysis was conducted. 1% critical damping, which was reduced from dynamic test result of the inflatable/self-rigidizable boom, was used for the analysis. 0.1-G step-function disturbance (lasted for two seconds) from spacecraft attitude control was used as the excitation force. Figure 12 gives the responses of the membrane center as well as the spacecraft. It is concluded that the disturbance from spacecraft attitude control can induce displacement of up to 0.065 centimeter at the center of the membrane. 0.065

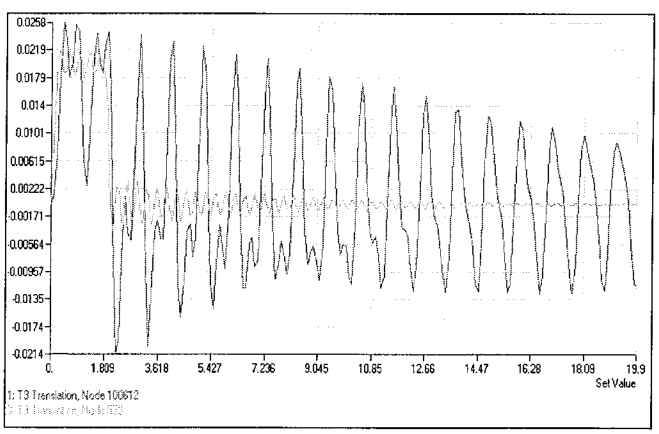

Figure 12. Transient analysis results

centimeter is about 0.07 of the wavelength and can cause 0.2 dB gain loss. It can also be concluded from Figure 12 is that the membrane motion will decay (i.e., be damped out) to less than 0.025 centimeter (0.027 wavelength; near-zero gain loss) in 18 seconds.

6. Future Tasks

In order to make the inflatable/self-rigidizable reflectarray antenna ready for space missions, some tasks need to be accomplished. Several tasks that have been planed for the near future will be discussed as following.

The first one of these tasks is the antenna launch constraining system. During the launch, the antenna has to withstand high acceleration, vibration, and acoustic impact. In order for the antenna to survive the launch, a constraining system is essential to hold the packaged antenna. The second task is the structural thermal distortion investigation. The space thermal environment is very harsh and could distort the inflatable structure. Consequently, it could degrade the flatness of the electromagnetic membrane. Therefore, the structural thermal distortion needs to be studied. The third task is studying the effects of damping on antenna's dynamic responses to spacecraft maneuvering. The sensitivities of damping locations will be investigated and extra damping will be applied to those most effective places. The fourth task is performing in-space deployment dynamics analysis. Due to the gravity, deployment dynamics test of a large inflatable space structure on the earth is almost not doable. Deployment dynamics analysis is therefore a necessary task for a space mission.

7. Conclusions

For a space mission, the launch cost is always a significant portion of the life-cycle cost. Launch cost is usually directly proportional to the launch volume and mass. Space inflatable technology is one of the emerging space technologies that can potentially revolutionize the design and applications of large space structural systems.

This paper discussed the development of an inflatable structure for the three-meter reflectarray antenna. This development has three stages. The first stage is a one-meter inflatable antenna. The second stage is a three-meter (horse-shoe) inflatable antenna. The third stage is a three-meter (movie screen) inflatable/self-rigidizable antenna. Detailed design of the "movie screen" antenna as well as functions of each major component have been discussed. Dynamic response analysis of the antenna to the spacecraft maneuvering has also been presented. The "movie screen" antenna used an inflatable/self-rigidizable technology so that any small leaks caused by materiel imperfection as well as micro-meteoroids impact would not affect the membrane performance and inflation air is no longer needed once the antenna is inflated. The differences among inflatable, inflatable/rigidizable, and inflatable/self-rigidizable have been discussed. An innovative inflatable/self-rigidizable technology, STA aluminum laminate boom, has been presented. Future tasks for the development of the inflatable reflectarray antenna have also been discussed.

8. Acknowledgments

The authors wish to thank Pierre Leung, Ubaldo Quijiano, Elvis Garay, Giovany Pelaez, and Joel Rodriguez, all of California State University at Los Angeles, for their contributions to this research effort. The work described was performed at Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration of United States.

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